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DETAILED CHARACTERIZATION OF THE INTERIOR BALLISTICS OF SLOTTED STICK PROPELLANT

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September 1984

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While classical, lumped-parameter modeling of granular propellant gun firings is often quite successful at reproducing experimental data, a similar treatment of stick propellant firings typically yields somewhat lower pressures and muzzle velocities than actually experienced in the gun. To identify those processes responsible for this behavior, a set of highly-instrumented gun firings has been performed in a 155-mm howitzer, using both stick and granular propellant charges. To simplify the investigation as well as to facilitate the analysis, a slotted, single-perforated stick propellant

was employed, and the granular propellant was prepared simply by cutting some of the sticks to a shorter length. Firings of the two types of charges yielded the same muzzle velocities, but with the stick charges operating at a 4% lower maximum chamber pressure. Detailed analysis of pressure versus time and travel profiles, obtained using fixed and on-board pressure instrumentation, along with concurrent multiphase flow (NOVA) simulations of the event, suggest two major contributors to the unexpected performance of the stick propellant charges. The first is an "artificial progressivity" resulting from higher post-peak chamber pressures associated with the more localized burning of the stick propellant (vis that of the longitudinally distributed, fluidized bed of granular propellant). The second is a hydrodynamic effect resulting from the non-Lagrangian pressure and velocity profiles exhibited by a stick propellant charge, again ultimately associated with the grossly discontinuous distribution of the burning stick propellant as opposed to the more continuous distribution of the granular propellant throughout most of the tube.

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I. INTRODUCTION

Numerous investigators have noted that slotted stick propellant appears to provide a higher muzzle velocity for the same charge weight than does 7-perforated, granular propellant.[1-3] At the same time, lumped-parameter modeling of experimental gun firings, typically quite successful in predicting the performance of granular propellant charges, has not provided similarly satisfactory simulations of stick propellant firings, even when the propellant has been slotted to minimize perforation-augmented burning processes.[1,3] The charge weight of stick propellant for a given performance level is usually predicted to be greater than actually required, with gun firings yielding higher pressures than expected for any given charge weight. This apparent increase in thermodynamic efficiency for stick propellant suggests that some mechanism must be involved beyond that of the influence of grain geometry on the mass generation profile. The investigation reported herein was devised to identify any such mechanisms.

II. EXPERIMENTAL

A carefully designed set of gun firings was conducted in a 155-mm howitzer (M199 Cannon) to demonstrate and quantify the increase in muzzle velocity obtained using stick rather than granular propellant. Slotted stick propellant was chosen for the test to eliminate perforation-augmented burning as a major factor in the combustion process,[3] and the granular propellant was obtained by simply cutting some of the stick propellant to a shorter length. Thus the compositions and form functions, as well as charge weights, were identical for both the stick and granular propellant charges tested, reducing the number of variables involved and simplifying the analysis. M30A1 propellant, Lot RAD 472-10, was employed, both as full-length, 737-mm sticks and cut into 25-mm-long grains, as shown in Figure 1. There were four charges made from the full-length stick (LS1,..,LS4) and four charges from the shortened "grains" (SS1,..,SS4); in addition, four standard (7-perforated granular) M203 charges were fired to provide baseline data. Propellant for the test charges (LSX and SSX) was weighed to 11.04 kg (either to within one SSX grain or by cutting one of the LSX sticks), a value previously determined in probe firings to give the appropriate M203 performance level. The standard M203 charges were all downloaded and brought to a weight of 11.84 kg (again, to within one grain). Further, packaging and igniter components for all three groups of charges tested were taken from one lot of M203 charges. Finally, inert-loaded M101 projectiles, adjusted to a weight of 43.08 kg and loaded to an average seating distance of 82.3 cm from the spindle face, were used for all the firings.

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[1] T.C. Minor, "Mitigation of Ignition-Induced Two-Phase Flow Dynamics in Guns Through the Use of Stick Propellant," ARBRL-TR-02508, Ballistic Research Laboratory, USA ARRADCOM, Aberdeen Proving Ground, MD, August 1983. ADA-133685.

[2] A. Grabowsky, S. Weiner, and A. Beardell, "Closed Bomb Testing of Stick Propellant Charge Assemblies," 17th JANNAF Combustion Meeting, CPIA Publication 329, Vol II, pp. 119-124, November 1980.

[3] F.W. Robbins and A.W. Horst, "Continued Study of Stick Propellant Combustion Processes," ARBRL-MR-03296, Ballistic Research Laboratory, USA ARRADCOM, Aberdeen Proving Ground, MD, July 1983. (AD A133004).

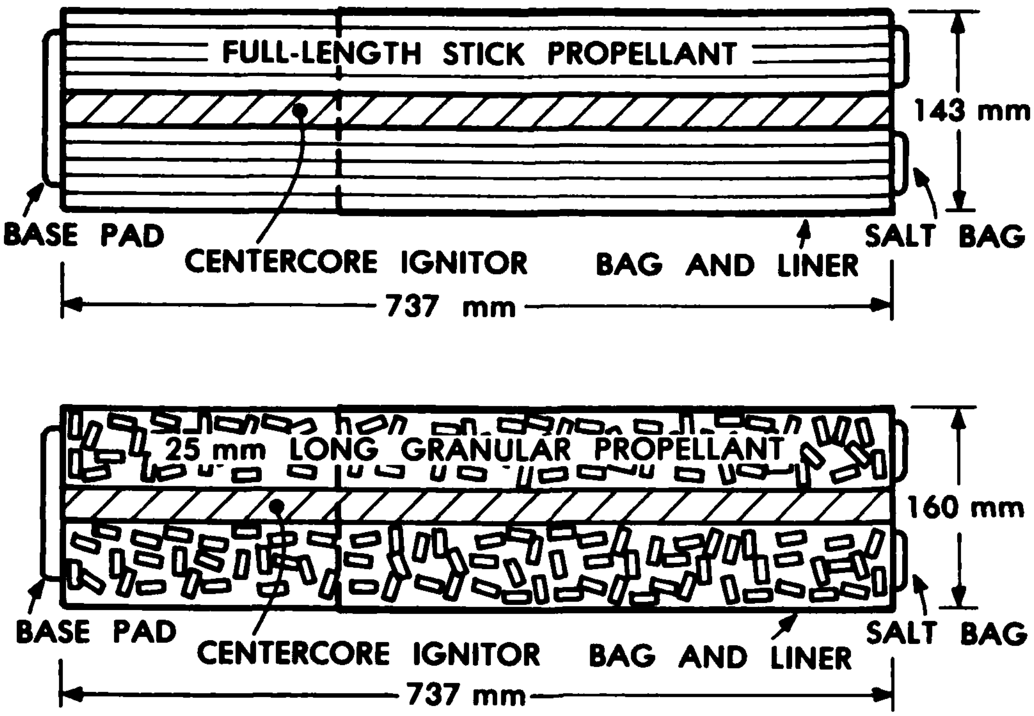

Figure 1. Configurations of Test Charges

The firings were performed at the Ballistic Research Laboratory's Sandy Point (R-18) Test Facility on 20 December 1982. The M199 cannon was instrumented with twelve Kistler 607C2 pressure gages (two each at three axial locations in the chamber and six at downbore locations, as shown in Figure 2). The same gages and instrumentation components were employed throughout the tests in order to best capture the relative differences among groups. A Doppler velocimeter was used to measure in-tube velocities, and induction coils were employed to determine muzzle velocities. Subsequent testing was also performed using telemetry-instrumented projectiles to provide on-board measurements of projectile base pressure and acceleration throughout the in-bore trajectory.

In support of this investigation, closed bomb firings were also conducted to determine burning rates for the RAD 472-10 propellant. Testing was done with the shortened, 25-mm-long grains and, since the propellant was slotted, the data were assumed to be applicable to the full-length sticks as well. A composite of results from four closed bomb firings, along with measured grain dimensions and calculated thermodynamic data, is provided in Figure 3.

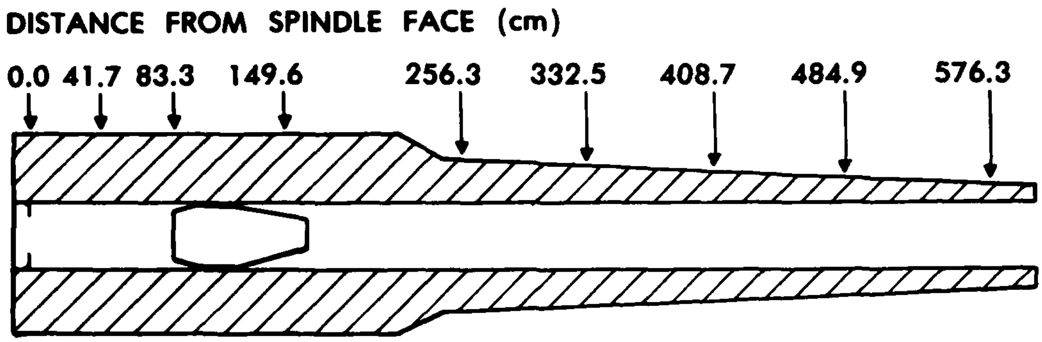

Figure 2. Locations of Pressure Gages in 155-mm, M199 Cannon

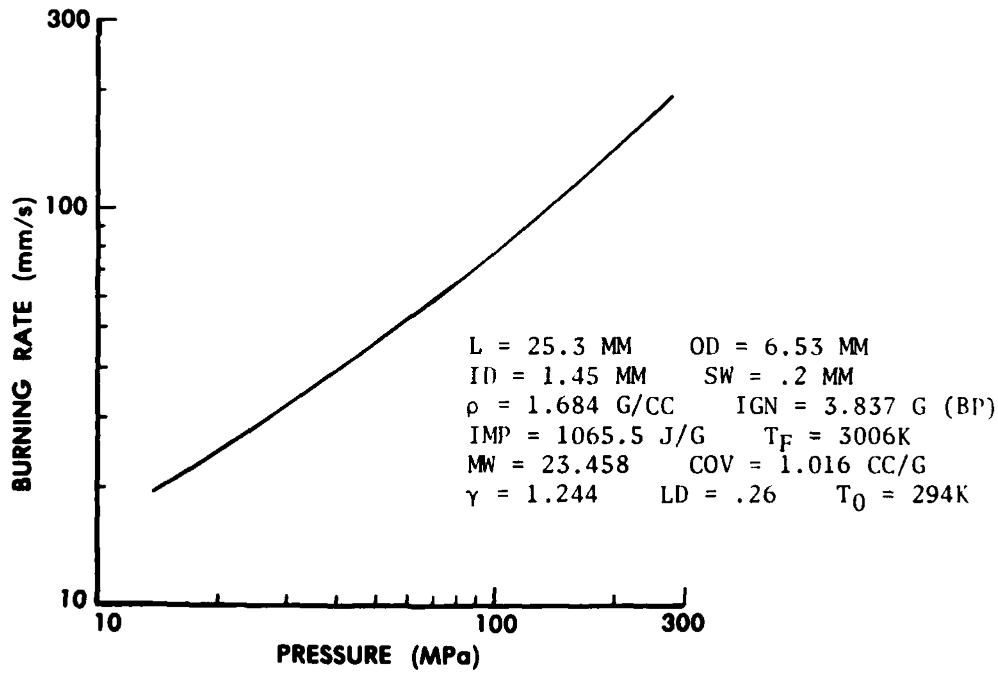

Figure 3. Burning Rate of M30A1 Propellant, Lot RAD 472-10

III. RESULTS

Muzzle velocities and maximum breech pressures for the three configurations are tabulated in Table 1.

TABLE 1. SUMMARY OF FIRING DATA

Type	Maximum Breech Pressure (MPa)	Muzzle Velocity (m/s)	Type	Maximum Breech Pressure (MPa)	Muzzle Velocity (m/s)	Type	Maximum Breech Pressure (MPa)	Muzzle Velocity (m/s)
SS1	347.8	815.8	LS1	335.7	815.1	M203	330.1	823.8
SS2	349.5	815.0	LS2	333.3	813.5	M203	326.3	818.8
SS3	344.3	812.0	LS3	335.5	813.5	M203	324.9	817.2
SS4	346.5	812.5	LS4	330.2	814.3	M203	329.8	820.7
Average values:								
SSX	347.0	813.8	LSX	333.7	814.1	M203	327.8	820.1
Standard deviations:								
	(2.19)	(1.86)		(2.56)	(0.55)		(2.58)	(2.84)

Table 2 provides a compilation of the average maximum pressures recorded at each gage location. Values for the first four provide the loci of maximum pressures for the chamber and rear portion of the tube. The gages at positions greater than 149.6 cm are uncovered after maximum chamber pressure occurs; values reported at these locations provide data needed for construction of a downbore base pressure versus travel curve.

TABLE 2. MAXIMUM PRESSURES AT SPECIFIED GAGE LOCATIONS

DISTANCE FROM SPINDLE (cm)	PRESSURE FOR SSX (MPa)	PRESSURE FOR LSX (MPa)
0.0	347	334
41.7	332	321
83.3	322	296
149.6	302	290
256.3	189	189
332.5	142	143
408.7	109	117
484.9	90	92
576.3	65	67

A final presentation of experimental data is given in Table 3, which provides, as a function of projectile travel (determined by passage of the various downbore gages), average values of pressure recorded at the breech and at the appropriate downbore pressure gages. These data were then used to establish discrete-time, breech and projectile base pressure versus travel curves for subsequent, detailed comparison of stick and granular slotted propellant firings.

TABLE 3. BREECH AND PROJECTILE BASE PRESSURES AS A FUNCTION OF TRAVEL

PROJECTILE TRAVEL (cm)	BREECH PRESSURE (MPa)		PROJECTILE BASE PRESSURE (MPa)	
	SSX	LSX	SSX	LSX
58	333	328	302	290
165	216	231	189	189
241	160	163	142	143
318	114	111	109	117
394	92	88	90	92
485	71	71	65	67

IV. ANALYSIS AND DISCUSSION

The above firings were modeled using both a lumped-parameter interior ballistic computer code (IBHVG, a descendant of the Baer and Frankle code),[4] and a one-dimensional, two-phase flow interior ballistic code (NOVA).[5] All input parameters were independently determined. Values for the burning rates, the thermodynamic parameters, the barrel resistance curve, and the chamber dimensions were identical for each code. Additional inputs required for the NOVA code (e.g., friction factor, Poisson ratio, and the speed of sound in the solid aggregate) were again determined from independent measurements or taken to be the best available values. In an attempt to maintain use of the same data bases, neither code considered the presence of the salt bag or other parasitic components. The major difference in treatments thus dealt with the lumped-parameter (i.e., "well-stirred") Lagrangian picture of the gas-solid mixture provided by IBHVG versus the full multiphase flow description of NOVA (including flamespread, detailed treatment of pressure gradients, and explicit recognition of propellant motion). A comparison of calculated and experimental results is provided in Table 4.

[4]P.G. Baer and J.M. Frankle, "The Simulation of Interior Ballistic Performance of Guns by Digital Computer Program," BRL R 1183, USA Aberdeen Research and Development Center, Ballistic Research Laboratories, Aberdeen Proving Ground, MD, December 1962. AD-299980.

[5]P.S. Gough, "Extensions to NOVA Flamespreading Modeling Capacity," PGA-TR-81-2, Paul Gough Associates, Inc., Portsmouth, NH, April 1981.

TABLE 4. COMPARISON OF CALCULATED AND EXPERIMENTAL RESULTS

	GRANULAR (SSX)		STICK (LSX)	
	BREECH PRESSURE (MPa)	MUZZLE VELOCITY (m/s)	BREECH PRESSURE (MPa)	MUZZLE VELOCITY (m/s)
EXPERIMENTAL	347	814	334	814
IBHVG	348	816	327	808
NOVA	342	816	332	821

We note that IBHVG predicts that the muzzle velocity for the stick firings should be 8 m/s less than for the granular, yet the experimental values obtained were the same. The probability of the velocity difference actually being greater than 4 m/s, assuming normal populations and using the standard deviations from Table I, turns out to be less than 0.1%, suggesting this disparity to be significant. An accepted use of lumped-parameter interior ballistic codes is the design of propellant grain geometry. After matching results to an existing set of firings, calculations are then typically performed with different propellant grain geometries with the expectation that the calculated changes in the maximum pressure and velocity will be correct, both in direction and in approximate magnitude. This is not the case here, where IBHVG results indicate a need for other physics beyond that associated only with the influence of grain geometry on the mass generation profile. The NOVA calculations, while not providing quite as good a match to the granular propellant firing data as does IBHVG, do suggest the influence of some such additional physical process, since an increase in velocity at a reduced maximum pressure is indicated for the stick charge.

Some insight into this difference between granular and stick propellant charge phenomenology can be gained by a detailed comparison of the experimental data to corresponding NOVA calculations, which allow us to infer information, such as gas-velocity profiles and solid-phase motion, not easily measured in the gun. First of all, we note from these (Table 2) and earlier firings that the loci of maximum pressures in the gun chamber and rear portion of the tube are quite different for the two propellant geometries. More structure is noted with the stick charge, even though recorded maxima occur within 0.5 ms of one another. As revealed in Figure 4, NOVA simulations capture this effect quite well.

This additional structure appears to accompany the formation of a large region of ullage which opens up between the forward boundary of the bundle of stick propellant and the base of the projectile as it moves down the bore and leaves the propellant behind. This event might be compared to a sudden enlargement in the cross-sectional area of a pipe through which gas is flowing. The same effect is not predicted to occur with granular propellant because increased interphase drag forces tend to distribute the propellant throughout most of the region, both eliminating the discontinuity in area and providing mass addition (via combustion) in this forward region as well.

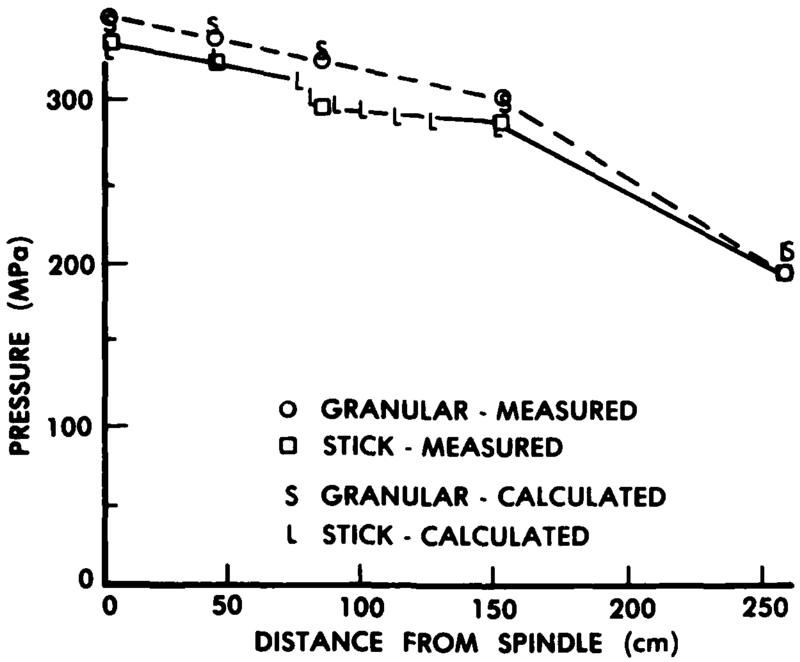

Figure 4. Loci of Maximum Pressures

Figure 5, constructed from the data of Table 3, also calls attention to the fact that breech pressures after the time of maximum chamber pressure are higher for the stick than for the granular propellant. Such behavior is usually attributed to a more progressive grain geometry. However, NOVA code results suggest another mechanism to be operative in this case, again finding its origin in the reduced propellant motion, more than in the different burning surface profile, associated with the stick geometry. While initial loading densities for stick and granular charges may be the same, after significant projectile motion, the "effective" loading densities might be quite different. The well-dispersed granular propellant can then deposit its combustion products throughout most of the volume between breech face and projectile base, but the stick propellant (as long as it remains intact) must burn in a far more localized region, with a finite time required to communicate information about this local accumulation of gases to distant portions of the tube (similar to a nozzleless rocket). This same effect was also observable upon comparison of experimental breech pressure versus time curves for the granular and stick firings (not shown here).

We next call attention to the fact that, if we plot the discrete data for experimental base pressure versus projectile travel (see Figure 6), the pressure at the base of the projectile for the stick firings shows an unexpected rise corresponding to the 327-cm position. The NOVA simulations again allow us to interpret this event. Since the stick firings show a slightly lower peak breech pressure but a higher breech pressure shortly thereafter (as explained above), predicted values of projectile travel at burnout turn out to be within 15 cm (262 cm for stick versus 277 cm for

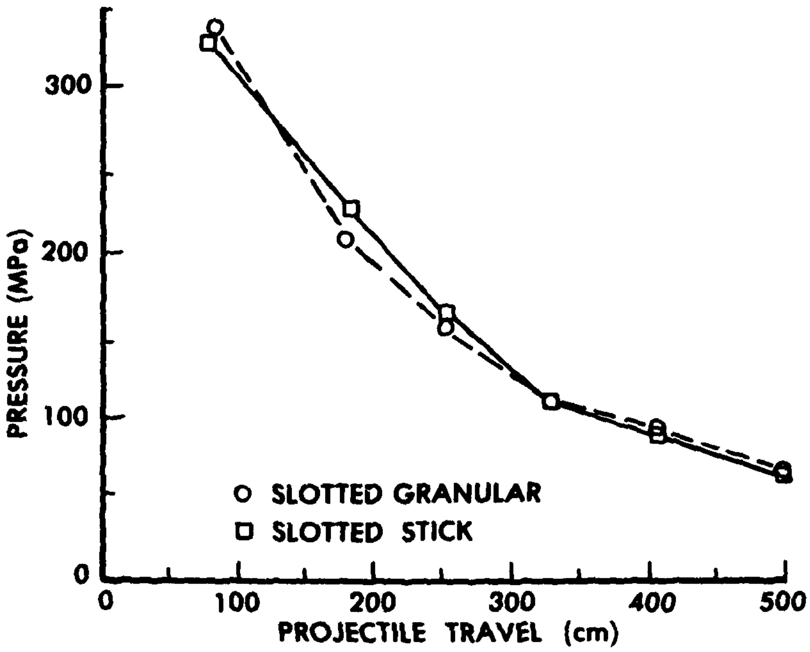

Figure 5. Breech Pressure Versus Travel - Experimental

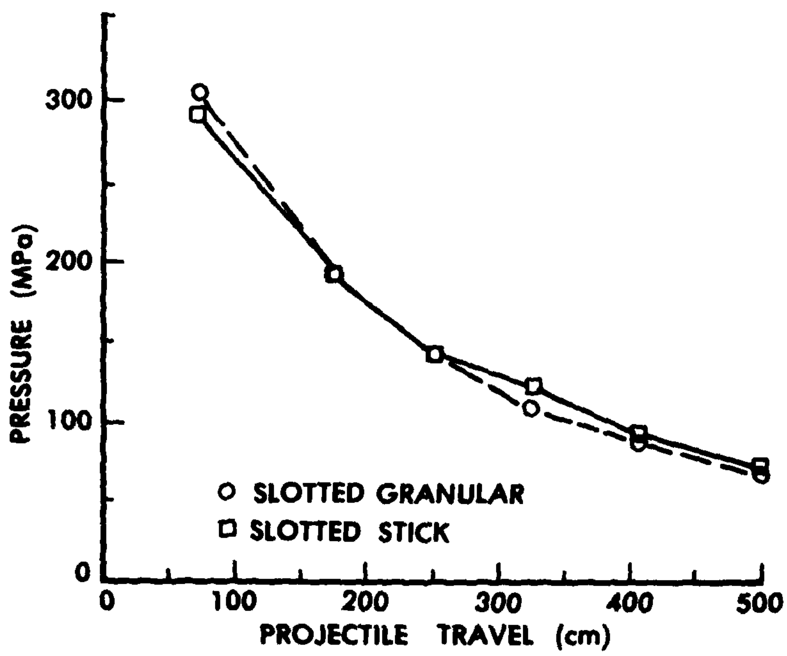

Figure 6. Projectile Base Pressure Versus Travel - Experimental

granular) of one another. Even when the projectile accelerated by the stick charge reaches the same position (277 cm), NOVA predicts it to be moving 5.5 m/s slower. (Doppler measurements performed during this program corroborated this trend.) Why then, after burnout, does the projectile continue to be accelerated faster for the stick charge than the granular charge? We recall that Figure 6 previously confirmed a higher downbore pressure for the stick propellant charge long after burnout. Again, we formulate a hypothesis associated with the discontinuous distribution of stick propellant in the gun tube, throughout its burning. We already noted its impact on pressure-distance profiles in the gun chamber (Figure 4); NOVA simulations reveal, in addition to this structure in the pressure field, a highly non-Lagrangian gas-velocity profile at burnout, shown in Figure 7, as well. Subsequent hydrodynamics can be assured to propagate this structured environment downstream, resulting in a temporarily increased acceleration relative to that encountered by the projectile experiencing the more "Lagrangian" environment provided by the granular propellant charge. Figure 8 shows the calculated gas-velocity profiles at the moment the projectile exits the muzzle.

Finally, we add that pressure- and accelerometer-instrumented projectiles were also fired using both the LSX and SSX charges. Figure 9 displays breech and on-board base pressure versus distance profiles for these firings, confirming the earlier results provided by discrete-location gages. Note particularly the excess in base pressure over that at the breech when the projectile is at about 300 cm of travel. Corresponding NOVA results are provided as Figure 10. Experimental and calculated pressure versus travel data for the granular charge, displayed in Figures 11 and 12 respectively, reveal profiles more nearly approximating the classical form.

V. CONCLUSIONS

Based on a detailed analysis of the experimental data described above, with added insight provided by concurrent NOVA code simulations of the firings, we conclude that there are two major contributors to the higher performance efficiency exhibited by stick propellant in large-caliber guns. The first is an "artificial progressivity" resulting from higher post-peak chamber pressures associated with the more localized burning of the stick propellant (as opposed to that of a longitudinally distributed, fluidized bed of granular propellant). Thus, while the initial loading densities of the two charges may be nearly identical, the "apparent" free volume associated with burning of the stick propellant after significant projectile motion may be significantly less than that for the granular propellant charge. The net results are higher local pressures and faster burning of the propellant remaining after peak pressure, allowing more time to extract "work" from the combustion gases. Interestingly enough, though this phenomenon is related to the reduced interphase drag of the stick geometry which leads to less motion of the solid phase, this behavior may still be considered a classical effect, in that its influence may be accounted for, to some extent, in a classical, lumped-parameter interior ballistic model by simply altering the pressure at which the propellant burns from the space-mean pressure to some value more representative of the local environment. (An accompanying change in the energy equation to reduce the contribution assigned to the kinetic energy of the solid phase is also recommended.)

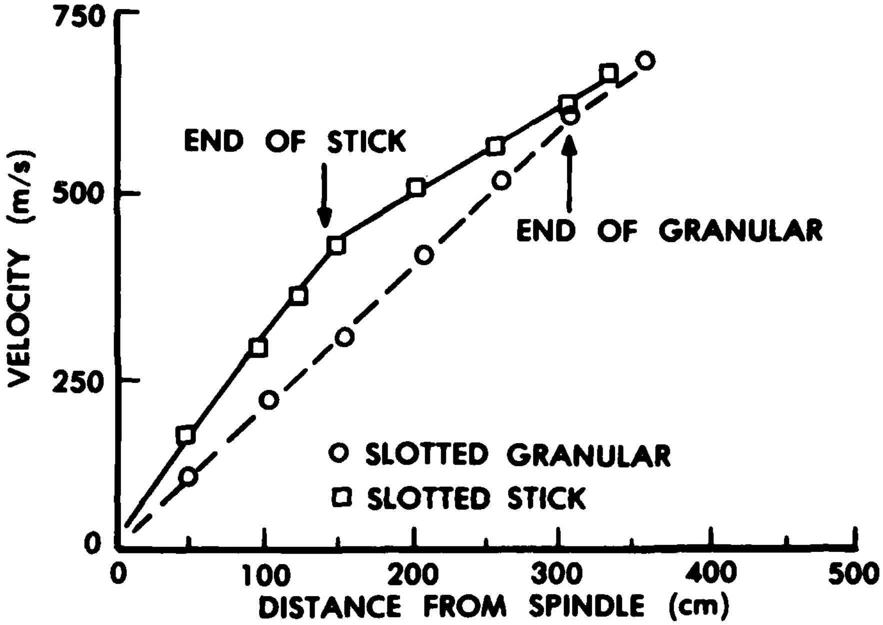

Figure 7. NOVA Predictions of Gas-Velocity Profiles at Propellant Burnout

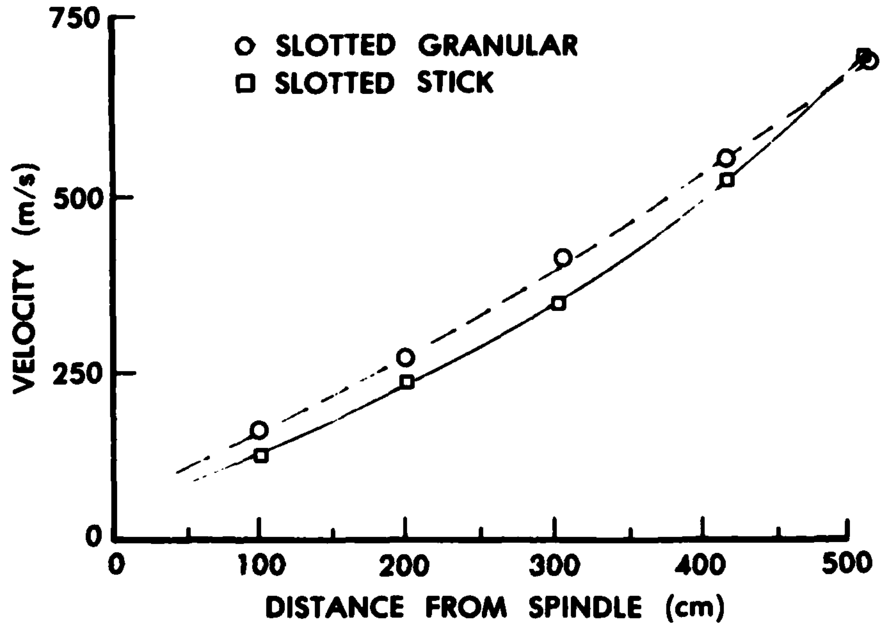

Figure 8. NOVA Predictions of Gas-Velocity Profiles at Projectile Exit

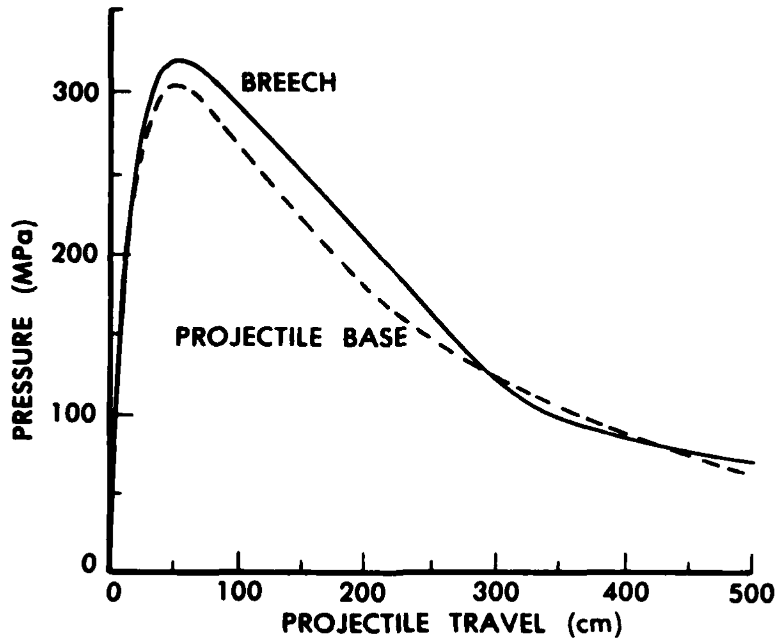

Figure 9. Breech and On-Board Projectile Base Pressures Versus Travel for a Stick Propellant (LSX) Charge

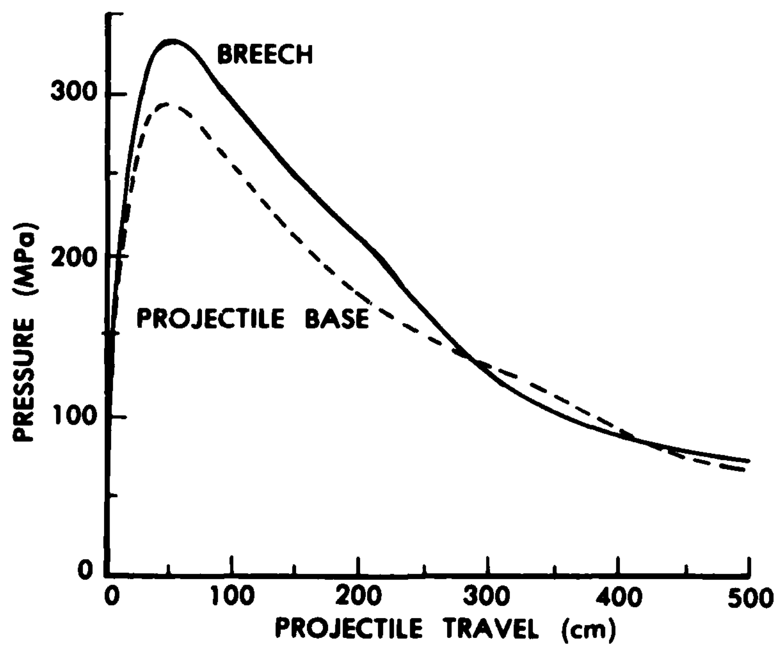

Figure 10. NOVA Prediction of Breech and Projectile Base Pressures Versus Travel for a Stick Propellant (LSX) Charge

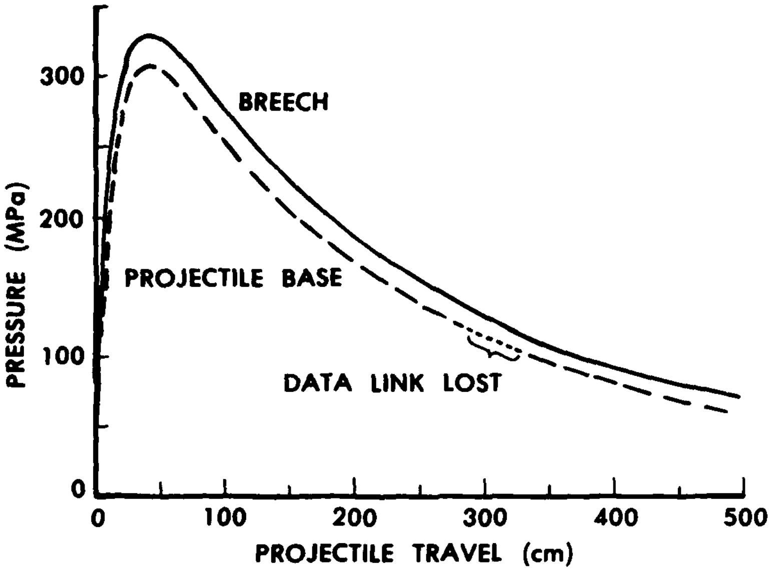

Figure 11. Breech and On-Board Projectile Base Pressures Versus Travel for a Granular Propellant (SSX) Charge

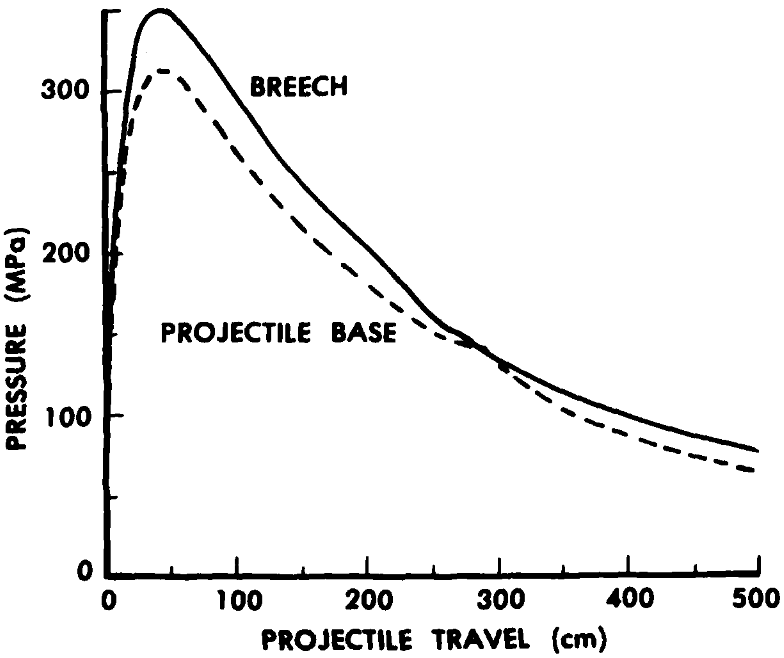

Figure 12. NOVA Prediction of Breech and Projectile Base Pressures Versus Travel for a Granular Propellant (SSX) Charge.

The second effect finds its origin in this same difference in the distribution of the solid phase between stick and granular propellant during the combustion phase; however, it clearly requires a hydrodynamic treatment of the interior ballistic cycle to estimate its importance. This phenomenon might be most easily understood by considering the nature of the gas velocity and pressure profiles in the tube at the time of propellant burnout. In the case of the granular propellant, a "Lagrangian" picture prevails: a nearly linearly increasing velocity profile between breech face and projectile base, with no abrupt changes in slope, with a correspondingly smooth, monotonically decreasing pressure profile. Conditions at burnout for the stick propellant charge are, however, quite different. Data presented in the previous sections reveal significant structure in the pressure profile, with the NOVA code providing similar information about the expected gas-velocity profile as well. If one considers these two pictures (i.e, stick versus granular profiles at burnout) as differing initial conditions to an ensuing single-phase, hydrodynamic event, it is quite easy to determine that the velocity of the projectile launched by the stick propellant charge upon muzzle exit may conceptually be higher or lower than that obtained with the granular charge, depending on the length of the gun tube. In the few, large-caliber systems studied to date, however, the stick propellant charge has always provided the higher muzzle velocity.

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